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Indoor Positioning with an Enterprise Radio Access Network

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Abstract

We introduce an indoor positioning technology based on an enterprise 3G UMTS radio access network and unmodified mobile phones. We describe the architecture and operation of a prototype that we have developed, and present empirical operational results from multiple enterprise settings. We discuss the relative advantages of using an enterprise RAN platform for indoor positioning, and examine both the challenges shared with alternative RF-based positioning technologies (e.g., WiFi), as well as the new and unique challenges that indoor cellular introduces. Finally, we present empirical results on location accuracy, and discuss how we seek to further improve accuracy using smartphone-based sensors and multiple radios.

Selection and peer-review under responsibility of Conference Program Chairs
Keywords: localization; small cells; location privacy; indoor navigation; femtocells; tracking

1. Introduction

Despite decades of research on indoor positioning schemes[1] exploring a diverse set of technologies[2,3,4], the growth of deployed systems has been modest when compared to the rapid adoption of outdoor positioning systems. But the promise of indoor or ’venue-based’ Location Based Services (LBS) remains large, both in commercial settings such as retail shopping malls and stadiums, and in enterprise campus environments. The large-scale deployment of IEEE 802.11x Access Points (APs) and network interfaces on devices has encouraged many researchers to focus on indoor WiFi Positioning Systems (WPS). The key advantage of this approach is the re-use of existing communications

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infrastructure, hence limiting costs for dedicated positioning infrastructure. Yet even with ubiquitous infrastructure and the rapid adoption of smartphones in the past decade, WPS deployments have grown slowly.

Recently, however, enterprise networking infrastructure has begun to shift in response to the ever growing numbers of Bring Your Own Devices (BYOD). In particular, enterprise Radio Access Networks (eRANs) and Distributed Antenna Systems (DAS) are gradually supplementing WiFi networks as alternate, seamless, and easily accessible indoor communications options. Hence we are motivated to take the unconventional approach of investigating how traditional macrocell positioning schemes[5,6] fare in indoor UMTS RAN settings. We describe a complete system we implemented and deployed that supports both feature phones and smart phones, with no change to *3GPP* protocols or additional software required. We use existing Radio Resource Control (RRC) layer signaling[7] to determine mobile device location. Our system offers several compelling advantages over WiFi-infrastructure based systems, including the promise that enterprise site occupants may be more likely to be *continuously connected* via cellular than WiFi, increasing the utility of location based and context-aware services. In addition, each user's subscriber and device identifiers (i.e., IMSI, IMEI) serve as a simple, unique and reliable identity that also facilitates querying other enterprise and cloud-based information systems (e.g., Google contacts, Exchange servers).

This paper explains how we have implemented eRAN localization, and highlights how the problems that arise in indoor cellular are distinct from those observed in other RF-based indoor positioning systems (e.g., WPS). Our key contributions are:

1. a detailed description of a system prototype we constructed and tested in several diverse enterprise environments, and
2. a discussion of the advantages and disadvantages of eRANs as a localization infrastructure, and
3. an evaluation of location accuracy based on test results, and
4. a discussion of the unique technical challenges with indoor cellular positioning that we have encountered and overcome.

The remainder of the paper is organized as follows. Section 2 describes our system architecture, operation and design. Multilateration algorithms and their behavior are presented in Section 3. Section 4 examines the many factors that determine location accuracy, focusing on those that uniquely occur in eRAN settings, and presents positioning accuracy results that we observed in various settings. We compare our work with related research in Section 5 and in the final section we summarize our contributions, and identify several envisioned enhancements of our positioning approach.

2. System Architecture, Design, and Operation

Our localization system was architected to work with unmodified 3G-capable feature phones and smartphones. This section describes how we used existing 3GPP protocols in the context of a UMTS enterprise radio network to determine User Equipment (UE) position. Figure 1 shows an unmodified 3G mobile device communicating with wireless APs called *Radio Nodes* (RNs) located throughout the enterprise. Each RN is connected to a RAN controller, with a backhaul connection to a mobile operator. In a ideal topology, RNs are placed to provide complete site transport coverage (with minimal building exterior signal leakage) while providing accurate, uniformly consistent location service. The UMTS Common Pilot Channel (CPICH) is used for transmission measurements between an RN and a UE. The signal *path loss* is calculated as the difference between the absolute Primary CPICH transmission power and the Received Signal Code Power (RSCP), measured in 0.5 dBm increments. Other measurements such as CPICH Ec/No (ratio of received energy per PN chip to total received power spectral density) may also be used in calculating UE position. A co-resident commodity processing platform hosts system application components on virtual machines. Depicted are two key service components we have developed; a Location Engine (LE), and one of multiple backend enterprise location-driven applications. A typical backend enterprise might be an offline footfall analysis of site occupants' cafeteria arrivals and departures. Alternately, a mobile device user might run an online venue application to map their real-time position on the site's building layout.

Operation of our location determination algorithm is as follows:

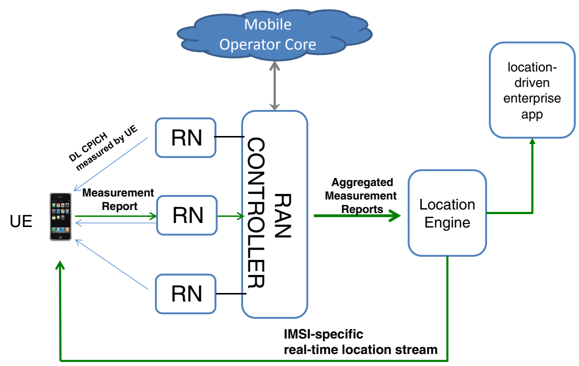


Fig. 1: Architecture of an eRAN-based positioning system.

1. Each connected UE generates an RRC layer Measurement Report (MR)[7] each second.
2. The eRAN controller receives and processes MRs and exports an LBS data stream to the LE.
3. The LE extracts signal measurements (e.g., path loss) between each UE (IMSI) and reachable RN.
4. Using known RN locations, each second the LE performs a first-order linear optimization to multilaterate each UE position.
5. The current calculated position for each UE is passed through history, smoothing, and domain knowledge filters to refine the estimate.
6. Each UE position is forwarded from the LE to an LBS for display, storage, or processing.

The multilateration operation is described next.

3. Multilateration

A signal's path loss p (dBm), or the loss in strength of a transmission of frequency f (Mhz) over a distance d (m), is approximately given by the free space path loss equation[10]

$$p = \frac{20}{\ln(10)} ln(d) + 20 \log_{10} f - 27.55. \tag{1}$$

We may alternately write the inverse of Eq. 1 as

$$d = e^{(p-\beta)/\alpha}, \tag{2}$$

where the parameter values are chosen by curve-fitting after measuring distance and pathloss between a UE and RN on site (e.g., $\alpha \approx 8.68, \beta \approx 38.19$).

Suppose we describe our environment with a 3-dimensional cartesian coordinate system. Given n radio nodes with locations (x_i, y_i, z_i), we estimate the location of a chosen UE at $(\hat{x}, \hat{y}, \hat{z})$. In each second the system measures the path loss, $\tilde{p}_i$, between the UE and the i^{th} access point, and Eq. 2 provides an estimate of its distance $\tilde{d}_i$.

We assume that our current location estimate's access point distance equals our measurement based estimate, $\tilde{d}_i$, plus some error, e_i, i.e. $\hat{d}_i = \tilde{d}_i + e_i$. Our goal is to minimize the mean squared error

$$E\,(MSE) = \frac{1}{2} \sum_i e_i^2 = \frac{1}{2} \sum_i \left(\hat{d}_i - \tilde{d}_i\right)^2 \tag{3}$$

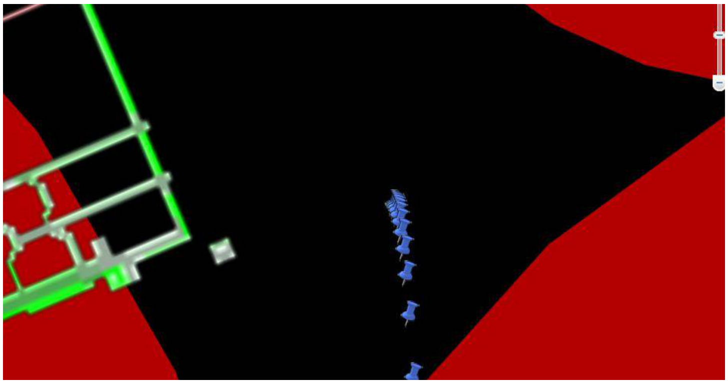


Fig. 2: Trajectory associated with a single location estimation optimization, with a blue pin placed at each step of the iteration. The initial location estimate (bottom) approaches the final position in 10 iterations. Red circles represent estimated distance from each of three RNs.

with respect to $\hat{x}$, $\hat{y}$, and $\hat{z}$. Our approach to this optimization is to apply gradient descent. We compute the gradient of E with respect to $\hat{x}$ as follows:

$$\frac{\partial E}{\partial \hat{x}} = \sum_i \left(\hat{d}_i - \tilde{d}_i\right) \frac{\partial \hat{d}_i}{\partial \hat{x}} \tag{4}$$

$$= \sum_i \left(\hat{d}_i - \tilde{d}_i\right) \frac{1}{2} \left((\hat{x} - x_i)^2 + (\hat{y} - y_i)^2 + (\hat{z} - z_i)^2\right)^{-1/2} 2\,(\hat{x} - x_i) \tag{5}$$

$$= \sum_i (\hat{x} - x_i) \left[1 - \frac{\tilde{d}_i}{\hat{d}_i}\right] \tag{6}$$

Finding the gradients of the remaining variables y, z proceeds similarly. We select a small constant step size c, with $c \ll 1$, and perform the descent by iteratively updating each coordinate estimate. For the x coordinate we have

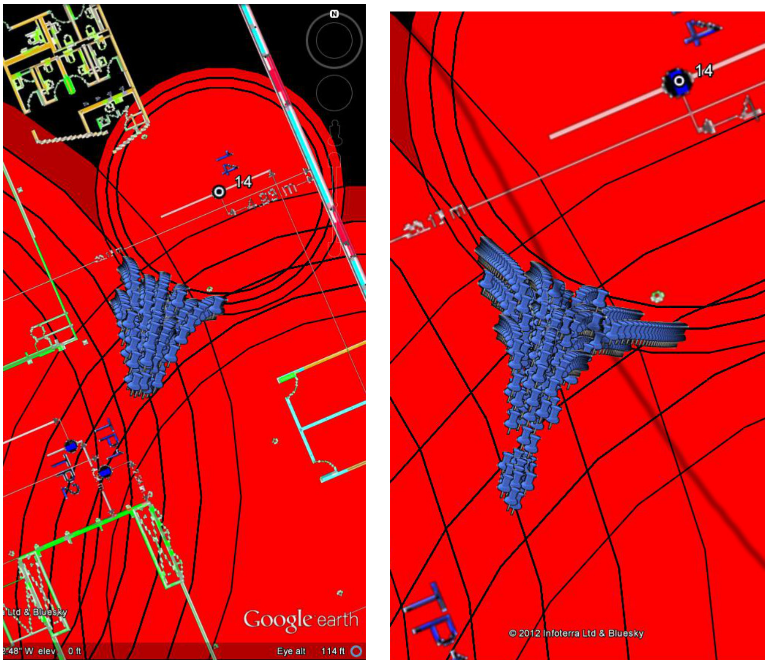
$$\hat{x} = \hat{x} - c\frac{\partial E}{\partial \hat{x}}, \tag{7}$$

and again the updates for the other coordinates follow similarly. The procedure is repeated until the solution converges or a maximum number of iterations are reached. Note that this optimization approach can potentially result in converging to a local minimum. Extensive testing suggests that the conditions required to exhibit this behavior are highly unusual, such as by initializing the descent at a point well outside of the building. To avoid this occurrence we 1) set the initial location of any newly arriving UE to be positioned at a location within the building, and 2) test that any calculated locations are feasible (inside the RAN coverage area).

Choosing a local coordinate system facilitates use of building layouts and assists with establishing landmarks. In the absence of a local coordinate system we rely on the fact that each RN – as with any macrocell – is configured with GPS coordinates, and alternately perform all operations in earth coordinates.

We have found that our optimization algorithm generally converges rapidly to within a small error such as $\epsilon < 0.1$ m. Convergence is accelerated by proper choice of an initial guess; initializations are typically chosen to be the location calculated in the previous second. Figure 2 shows how the estimated location ’flys in’ from a previous second’s location to a new estimate, depicted as a sequence of blue pins moving to the solution in 10 steps of decreasing size, corresponding to each algorithm iteration.

We have also experimented with various heuristics which optimize functions other than Eq. 3. We find, however, that great care should be taken, since side-effects can result. For example, it is intuitive to consider optimizing a weighted distance function, where weights are chosen to overweight RNs with the strongest signal (i.e., least path loss), which are presumably physically closer and likely to provide more accurate distance estimates. Figure 3a shows a collection of optimization trajectories taken over tens of seconds for a stationary UE; the concentric circles around each RN shows distance estimates for each measured path loss, which fluctuates each second over a ±1 dBm range



(a) Unweighted optimization (b) Weighted optimization

Fig. 3: Trajectories of an a) unweighted and b) weighted optimization for a stationary UE. In the unweighted optimization the final location estimates are found at different distances from the strongest RN. In the weighted optimization the final location estimates are pressed up more tightly around the strongest RN, but spread more widely, introducing positioning jitter.

even for a stationary UE; we can think of this as measurement noise. Figure 3b shows the optimization trajectories for the same data with a weighted optimization that overweights the stronger received signals. The weighting does indeed work as intended, with final locations pressed tightly in a circle around the strongest RN. But note these locations tend to 'spread out' over that circle relative to the unweighted optimization. Such an effect can increase the 'jitter' associated with the display of a position of a stationary UE, clearly an undesired effect.

4. Positioning Accuracy

4.1. Challenges

Indoor RF signal-strength based positioning techniques generally do not provide a high degree of location accuracy[8] (e.g., 5-7 m.) though many research groups have demonstrated that these accuracies can be improved significantly through techniques including radio mapping (i.e., fingerprinting) site surveys[19]. Next we review key impediments to high accuracy, some shared with alternate positioning systems (e.g., WPS) and others that uniquely manifest in a 3G RAN setting.

- *AP topology* Increasing the spatial density of APs is the primary mechanism to improve location accuracy since 1) distance estimation error from measured path loss decreases with a UE's proximity to an AP, and 2) positioning uncertainty decreases with increasing numbers of geographically diverse RN signal observations. An irregular AP physical topology is also desirable. For example, mounting more than 2 RNs along a common interior or exterior wall is common but often inadvisable, since such a layout provides limited orthogonal direction positioning information. Yet we find that these design rules are often violated when engineering a RAN for voice/data service without consideration of localization. Why? First, minimizing infrastructure cost tends to result in the fewest number of RNs possible serving the coverage area, lowering spatial density. Second, tapping into existing power and communications lines in rectangular buildings tends to encourage linear arrangements of RNs, typically pressed up against exterior building walls.

- *System Design* Cellular systems engineered for the macrocell environment contribute to accuracy limitations when used for indoor positioning. For example, permissible transmit and receive power ranges for voice equipment – and interference considerations – impose minimum separation requirements on RNs. Unlike other settings where signal strengths are commonly used, we observe that the set of RNs that are 'heard' by a UE may change frequently. The fluctuating presence or absence of an RN signal tends to cause an estimated position to 'bounce' either toward or away from the *flashing* RN. We commonly observe this as we approach a sufficiently large distance from an RN where the received signal is weak, where reception fluctuates as the signal comes in- and out-of-range.
- *Receiver Diversity & Use Model* The shrinking form factors of mobile devices – smartphones and tablets – have changed the way that mobile computing devices are used. Mobile devices being handled more frequently, and are far more portable than older devices such as laptops. The diversity of clients has also grown, and consequently so has the range of receiver performance characteristics.
- *Multipath and Obstructions* While models of conventional obstructions (e.g., furniture, cubicle walls) have been developed[10], we now confront devices that might be enclosed while operating normally (e.g., phones in pockets and purses) for which few obstruction models have been created. Shrinking device form factors and the pursuit of low cost designs have also imposed new constraints, such as limiting the use of multiple antennas to address indoor multipath. When turning an outside corner around an obstructing interior wall, an RN might come into LoS and be heard, while the signal from a previously heard RN might be lost, resulting in a change of 2 signals in a short timeframe, and perceived location jitter.
- *Models and Algorithms* Though our models incorporate some local site characteristics that improve the accuracy Eq. 1, the relationship between measured path loss and distance remains approximate. Figure 4 shows how we use site information encoded as an XML-based representation of floorplan regions that provide hints for positioning refinements (e.g., the nearest feasible location outside a *clip region* such as a closet, or position-specific signal strength adjustments for *obscured RNs*. While approaches using radio mapping or fingerprinting have been successfully used in other settings, their power to improve accuracy is somewhat limited in our intended uncontrolled setting due to changing device use models and receiver diversity. While algorithms can and do improve accuracy, this may come with certain tradeoffs. For example, algorithms that seek to minimize the perceived position jitter of a stationary UE might also lessen position responsiveness when the UE moves.
- *Handoffs* Unlike WiFi, handoffs occur relatively frequently as a UE moves quickly through a dense RN topology. As the set of 'heard' RNs change, perceived position jitter is a likely outcome.

```
<?xml version="1.0" encoding="UTF-8"?>
<Floorplan name="building1">
  <Floor id="2">
    <ObscuredNode>
      <VisibleNode id="56585843"/>
        <VisibleNode id="56585916" Pathloss-="2"/>
    </ObscuredNode>
    <ClipRegion clipMode="nearest" name="atrium">
      <Point x="37.23" y="15.74"/>
        <Point x="37.23" y="23.30"/>
    </ClipRegion>
  </Floor>
</Floorplan>
```

Fig. 4: Encoding of positioning hints from local site analytics.

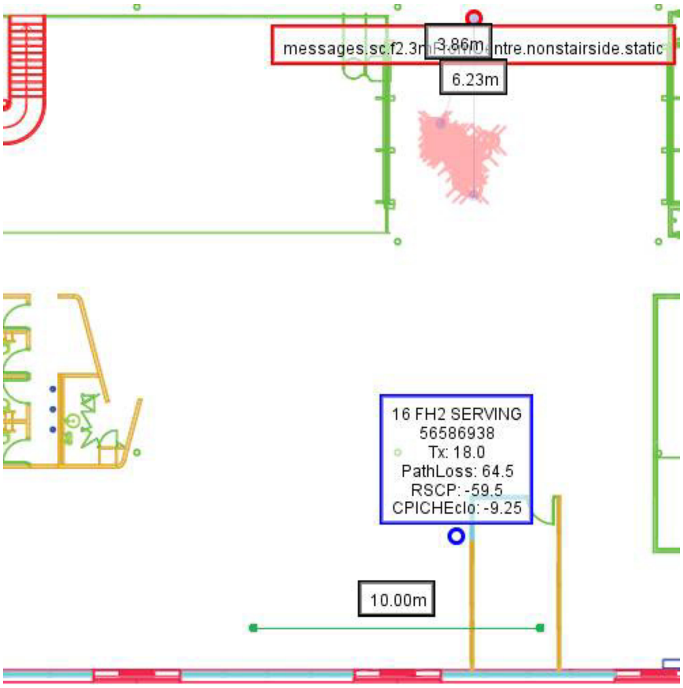


Fig. 5: Location cluster for a stationary UE in a system not designed for location service.

Because of these factors, accuracy is highly location-dependent throughout the coverage area. In general, we find that accuracy is highest either when a UE is 1) in very close proximity to an RN, or 2) roughly equidistant from a collection of 3 or 4 RNs. Nearness to external building walls is generally unfavorable, as are locations near to or outside the convex hull of AP locations.

4.2. Empirical Results

We next consider two specific but illustrative empirical results taken from 2 distinct sites. In the first building a RAN topology was designed exclusively for voice/data quality (i.e., no consideration of location service quality) using standard design rules. Figure 5 shows a cluster of estimated locations of a motionless UE taken over a 45 second interval, with each second's estimate represented by a cross-hatched pink circle. The actual UE location was at a test point marked by the red circle, located approximately 10, 12 and 13 meters from the 3 nearest RNs. The inter-RN separation was roughly 19 meters. The average location error – the distance between the actual location and the cluster centroid – is 4.91 meters. After examining many such cases of fixed and moving UEs in RANs not designed with location service as a consideration, we have developed a simple engineering rule of thumb used to estimate worst case location error: roughly 1/3rd the inter-RN separation. Having such a rule is not intended to predict performance reliably, rather it serves as an initial back-of-the-envelope approach to estimating the number of RNs needed for location service site coverage.

Fortunately, a few small changes to this RAN – the addition of a couple of nearby RNs, and rebalancing transmit powers – ensures better location accuracy. Figure 6 depicts one such example, where a set of test points is linked by a green line to indicate a well-served coverage area. The figure shows that the location error (RMSE) can be kept in a range of roughly 2-6 m. for interior building positions, depending on position and obstructions.

Let's next consider positioning during the course of a loosely structured walk depicted in Figure 7. Here a UE engaged in a voice call was walked between 2 RNs located overhead, lingering approximately 30 seconds under each. A weakly-defined cluster of location estimates is shown near each RN. The cluster variation is partly due to human

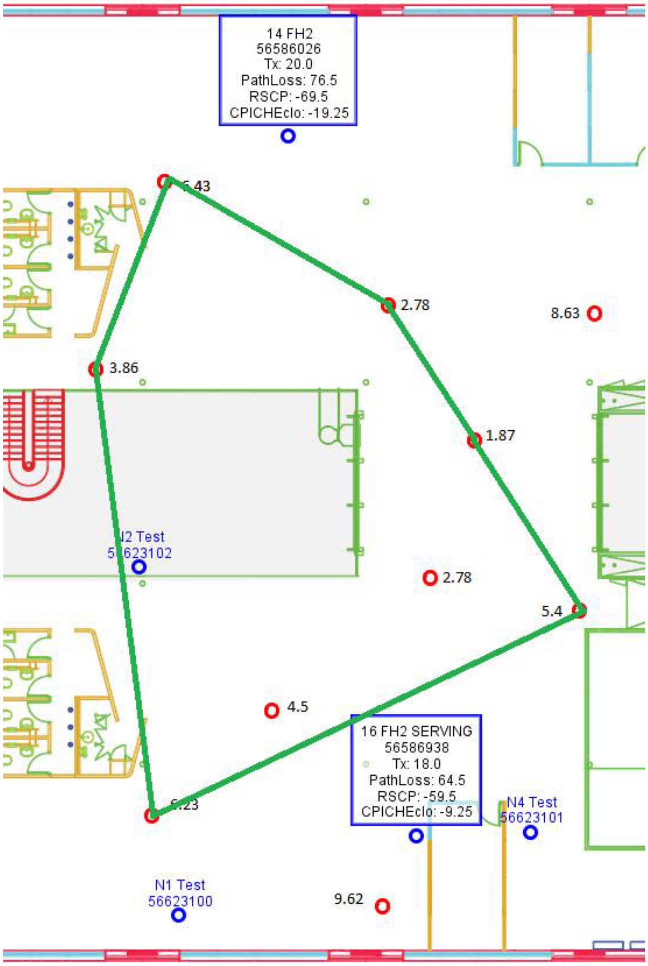


Fig. 6: Location error at a set of testpoints in a RAN reconfigured for improved location service.

behavior; a person holding a UE in an active call is hardly at rest. Note that estimated walk locations are characterized by a significant bias (approx. 3 m.) toward the upper left, which is the general direction of the other RNs in the system. Though not shown in the figure, when a UE is positioned under an RN a *near-far* capture phenomena occurs – the nearest RN's signal is so powerful that others are not heard. We have experimented with several algorithms which address this phenomena. For example, one such algorithm (not shown) recognizes this occurrence and places location estimates directly at the RN. We caution again, however, that such attempts to improve accuracy can have tradeoffs, such as decreased responsiveness as a user departs from under an RN.

Numerous other phenomena and system artifacts can be observed in the depicted walk. For example, the general bias of estimated locations toward the upper left arises in part for 2 reasons. First, the walk is along a segment of the convex hull formed by the RNs in this location, with all other RNs located to the upper left. Multilaterating with these hearable nodes tends to 'pull' the estimated location in the direction of those RNs. Second, the figure depicts only part of a longer walk which originated from the upper left as well. Since our positioning algorithms refine location estimates using past history, walking to a point and stopping tends to result in estimated positions that retain a small bias toward the direction of approach.

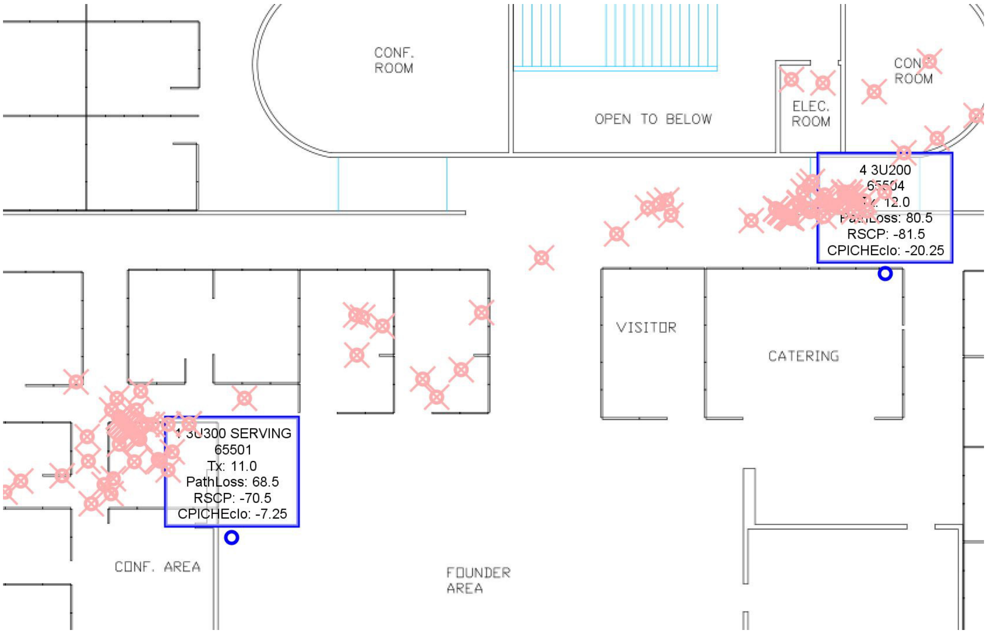


Fig. 7: Locations at 1 sec. intervals of a walk between RN 65501 (lower left) and RN 65504 (upper right) with tens of seconds lingering under each.

5. Related Work

The literature on indoor localization is vast, and extensive surveys[11,15,12,13,14,16] tend to partition the space by the underlying localization technology considered. Within RF-based approaches, considerable effort has been place in studying WPS in indoor environments[18]. Much recent effort has been focused on schemes that refine WPS accuracy, such as a clever approach to using collaborative crowdsourcing for fingerprinting [19] and approaches using physical layer information to overcome multipath to greatly improve location accuracy[20]. Yet the focus of research effort is constantly evolving, most recently with a surge of attention to BlueTooth Low Energy (BLE) based solutions for proximity applications[21].

Our work in this paper has focused attention squarely on positioning 3G/4G devices indoors. Localization of 3G phones in the macrocell environment has of course been well studied[17], and the potential role of the UMTS RRC layer for UE positioning indoors was discussed in[9]. Though networks of femtocells have been studied extensively[23] only recently has indoor positioning with this technology been considered directly[22,24,25].

6. Conclusion

We have proposed an approach to determining user position in enterprise settings using indoor RANs. A complete operational system has been developed, deployed and tested in multiple settings, and empirical results have been presented. We have described some of the unique challenges and opportunities that this emerging technology presents.

Indoor positioning systems appear to be poised for rapid growth, and we are seeing increased interest by industry participants. For example, the successful Google Maps is being extended to reach indoors[26]. The formation and growth of the *In-Location Alliance*[27] also indicates mounting activity. Yet there are also reasons to be cautious, as there is still considerable uncertainty around user acceptance and location privacy issues. We are cautiously optimistic about eRANs for localization for several reasons. First, our conjecture is that enterprise occupants will not only carry cellular devices, but these devices will remain connected almost always. This use model differs dramatically from user behavior with WiFi-only devices, which might have contributed to slower take-up of that technology for positioning. We also argue that RANs are particularly well suited to address the challenge of seamless indoor/outdoor positioning.

In contrast to the focus on indoor location accuracy pursued by the vast majority of research groups, we have directed our attention at crucial practical systems issues including scalability, security and privacy, and ease of deployment. This emphasis has allowed us to investigate novel problems, such as the placement of RNs to jointly optimize voice and data transport coverage and quality as well as location accuracy. The evolution of eRANs toward supporting multiple radios (e.g., WiFi, LTE) will permit us to employ in the future hybrid positioning schemes (i.e., radio diversity) to further improve location accuracy.

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